

DPF2015-291  
1 November 2015

# Precision QCD for LHC Physics: The nCTEQ15 PDFs

FREDRICK I. OLNES<sup>1</sup>

*Southern Methodist University, Dallas, TX 75275, USA*

*based on work in collaboration with*

D. B. CLARK, E. GODAT, T. JEŽO, C. KEPPEL, K. KOVAŘÍK, A. KUSINA,  
F. LYONNET, J.G. MORFÍN, P. NADOLSKY, J.F. OWENS, I. SCHIENBEIN,  
J.Y. YU

Searches for new physics at the LHC will increasingly depend on identifying deviations from precision Standard Model (SM) predictions. At the higher energy scales involved for the LHC Run 2, the heavy quarks play a more prominent role than at the Tevatron. Recent theoretical developments improve our ability to address multi-scale problems and properly incorporate heavy quark masses across the full kinematic range. These developments are incorporated into the new nCTEQ15 PDFs, and we review these developments with respect to sample Run 2 measurements, and identify areas where additional effort is required.

PRESENTED AT

DPF 2015

The Meeting of the American Physical Society  
Division of Particles and Fields  
Ann Arbor, Michigan, August 4–8, 2015

---

<sup>1</sup>Work supported in part by the U.S. Department of Energy under grant DE-FG02-04ER41299.

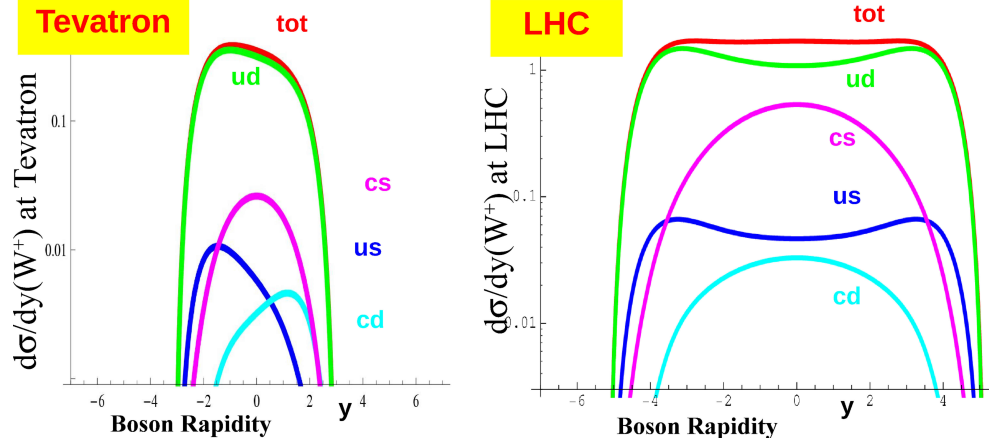


Figure 1: The leading-order (LO) differential cross section ( $d\sigma/dy$ ) for  $W^+$  production at the Tevatron (2 TeV) and the LHC (14 TeV) as a function of rapidity. The partonic contributions are also displayed for  $\{u\bar{d}, c\bar{s}, u\bar{s}, c\bar{d}\}$ . The vertical scales are logarithmic.

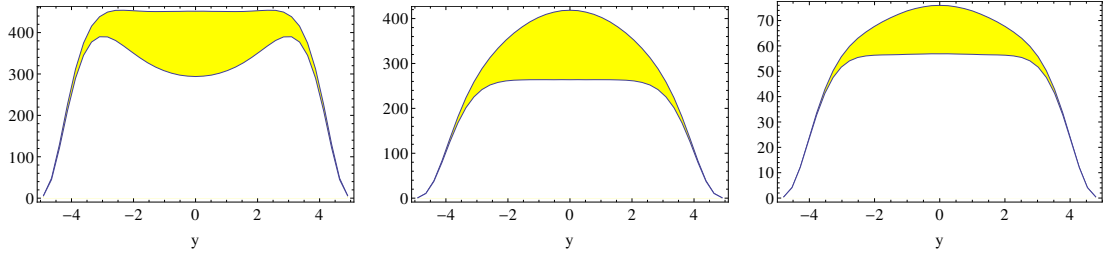


Figure 2: The strange quark contribution (yellow) as a fraction of the total  $d^2\sigma/dM/dy$  in pb/GeV for  $pp$  to  $W^+$  (left),  $W^-$  (center),  $Z$  (right) production at the LHC for 14 TeV with CTEQ6.6 using the VRAP program at NNLO. C.f. Ref. [2] for details.

## 1 Introduction

Our field has seen major discoveries in recent years from a variety of experiments, large and small, including a number recognized with Nobel Prizes. The recent performance of the LHC has exceeded expectations and produced an unprecedented number of events to be analyzed. On the Intensity Frontier, Fermilab is advancing a number of high-precision experiments (Muon  $g - 2$ , Mu2e), as well as expanding its neutrino program. Thus, there is a wealth of data to explore, and a comprehensive analysis requires the most advanced and innovative tools.

As the accuracy of the experimental measurements increases, it is essential to improve the theoretical calculations to match. If we can make detailed predictions of W/Z/Higgs production (for example), then we have the ability to distinguish a “new physics” signal from an uncertain SM background process. To determine if

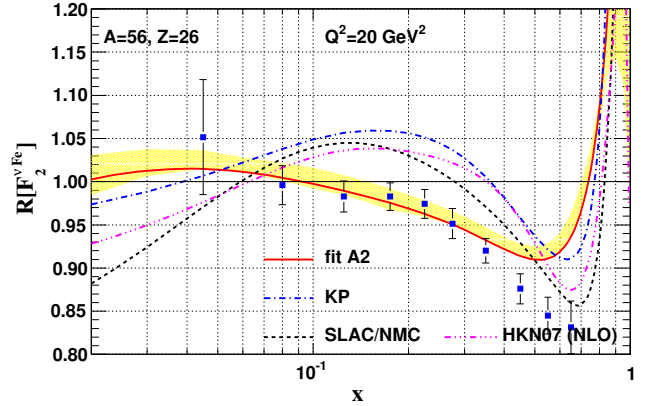
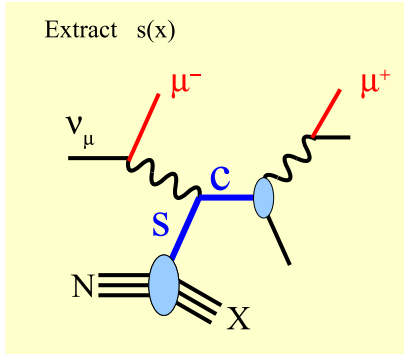


Figure 3: The computed nuclear correction ratio,  $F_2^{Fe}/F_2^D$  as a function of  $x$  for  $Q^2 = 20 \text{ GeV}^2$ . Figure-a) shows the basic dimuon process  $\nu N \rightarrow \mu^+ \mu^- X$ . Figure-b) shows the fit using the  $\nu N$  DIS data (fit A2) compared with parameterizations of the neutral current lepton ( $\ell^\pm N$ ) DIS data (KP, SLAC/NMC, HKN07). The data are from the NuTeV experiment. See Ref. [4] for details.

the newly discovered Higgs boson is that of the Standard Model (SM) or a more exotic type, we must study both the production cross section and various decay channels to make its proper characterization. In a complementary manner, the Fermilab high-intensity high-statistics experiments force us to reexamine previous assumptions (nuclear corrections, isospin and lepton-flavor symmetries) and require us to extend our calculations to increasingly high orders including subtle electroweak corrections. The key step for all the above analyses is to make accurate predictions, including realistic estimates of the underlying theoretical uncertainty. The PDFs are at the heart of this program.

## 2 PDF Flavor Determination & Heavy Targets

The objective of the nCTEQ project is to obtain the most precise set of Parton Distribution Functions (PDFs) to facilitate measurements and interpret hadronic processes at both fixed-target experiments, HERA, RHIC, Tevatron, and the LHC. The project began when it was realized that a limiting factor on the proton PDF precision was the nuclear corrections used for the wealth of nuclei data—particularly the DIS data which is crucial for flavor differentiation.

As the bulk of the data used in the global analyses of the PDFs comes from Deeply Inelastic Scattering (DIS) processes, much of this is measured on heavy targets (e.g., iron or lead) where nuclear corrections must be taken into account. This data is very important for distinguishing the separate flavor components in the proton.

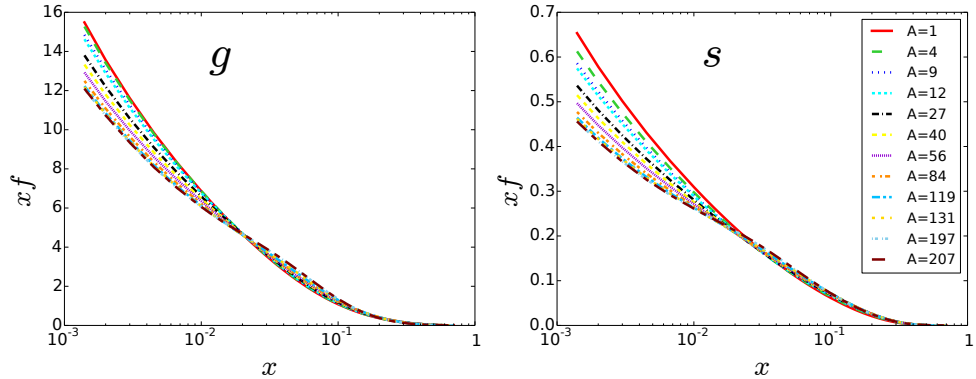


Figure 4: The nCTEQ15 [1] PDFs for selected nuclei for the gluon and strange PDF at  $Q = 10 \text{ GeV}$ .

Surprisingly, the strange quark PDFs have a large influence on LHC “benchmark” processes.

In Fig. 1 we note that the heavy quark initiated contributions ( $c\bar{s}$ ) at the LHC can be 30% or more of the total cross section, whereas it is only a few percent at the Tevatron. Furthermore, the larger  $\sqrt{s}$  energy of the LHC probes a much broader range in rapidity  $y$ , and hence a broader range in the partonic  $x$ . While the LO illustration of Fig. 1 is instructive, in Fig. 2 we show the high-precision results of the NNLO calculation for  $\{W^\pm, Z\}$  using the VRAP program; [5] if we are to make full use of this very precise NNLO result, we must improve the precision of the strange PDF.

The primary constraint on the strange quark PDF comes from neutrino-induced DIS dimuon production ( $\nu N \rightarrow \mu^+ \mu^- X$ ) on heavy targets.<sup>2</sup> Fig. 3-a) shows the basic dimuon process used to constrain  $s(x)$ ; the anti-neutrino process can constrain  $\bar{s}(x)$ . As the neutrino experiments use heavy nuclear targets (typically iron or lead), we need to know the nuclear correction to relate this information back to the proton data.

Fig. 3-b) shows the extracted nuclear correction factor for the neutrino DIS ( $\nu N$ ) processes (fit A2) as compared with that for charged lepton ( $\ell^\pm N$ ) DIS processes (KP, SLAC/NMC, HKN07), and we observe some significant differences. As was demonstrated in Ref. [3], if we properly incorporate the experimental correlated errors in the global PDF fit, we are unable to find a nuclear correction which is compatible with both the  $\nu N$  and  $\ell^\pm N$  data simultaneously;<sup>3</sup> thus, we must account for this

<sup>2</sup>New data from LHC are beginning to provide information the strange quark at larger  $Q$  and smaller  $x$ ; *cf.* Refs. [2, 6].

<sup>3</sup>Note that this difference was present *only* if we imposed the full constraints of the experimental correlated systematic errors; if the systematic and statistical errors were added in quadrature, a common correction factor was obtained. This observation highlights the importance of the experi-

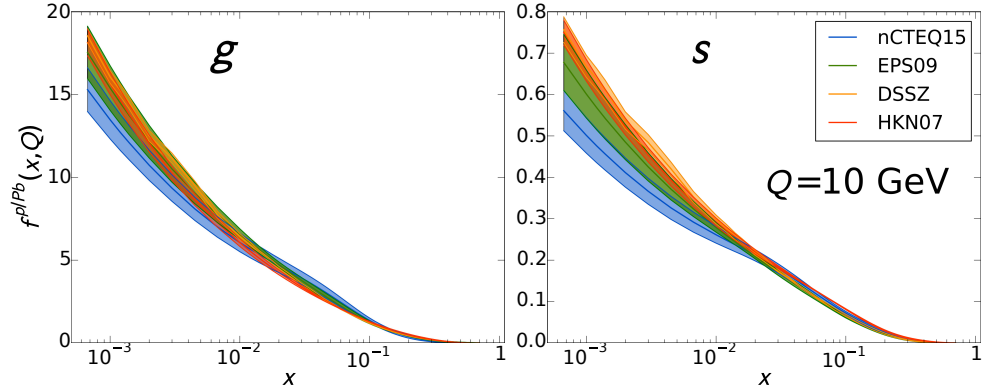


Figure 5: The nCTEQ15 PDFs showing the uncertainty bands for selected partons ( $g, s$ ). For comparison, we also show bands for HKN07, [7] EPS09, [8] and DSSZ. [9]

when we extract the strange PDF and include an additional uncertainty.

### 3 The nCTEQ15 PDFs

The nCTEQ framework allows the nuclear correction factors to be integrated *dynamically* into the fit to better identify tensions between data sets, and to extract more accurate PDFs when using data from nuclear targets. We have now released the nCTEQ15 PDFs with error sets which provide our results of the global analysis for all nuclear  $A$  values.<sup>4</sup> [1] In addition to the Deep Inelastic Scattering (DIS) and Drell-Yan (DY) processes, we also include inclusive pion production data to help constrain the gluon PDF. Within our framework we are able to obtain a good fit to all data.

Fig. 4 displays selected partons for a range of nuclear  $A$  values. We have determined the uncertainties using the Hessian method with an optimal rescaling of the eigenvectors to accurately represent the uncertainties for the chosen tolerance criteria. In Fig. 5 we compare the nCTEQ15 PDF uncertainty bands with other sets from the literature. While the general features are similar, there are some important differences. For example, the nCTEQ15 parameterization allows different correction factors for the up and down quarks. To investigate which data sets are driving this difference, we examine the correlation of the data sets with specific flavor components, and assess the impact of individual experiments. Fig. 6 shows the correlation  $\cos \phi$  for the up and down valence as a function of  $x$  for the lead PDFs at  $Q = 10$  GeV. Selected experiments are highlighted with symbols. To emphasize the fact that the

---

mental error treatment in the fits, and resolves a number of questions regarding the compatibility of these data sets.

<sup>4</sup>These are available on-line at the HepForge repository: <http://ncteq.hepforge.org/>

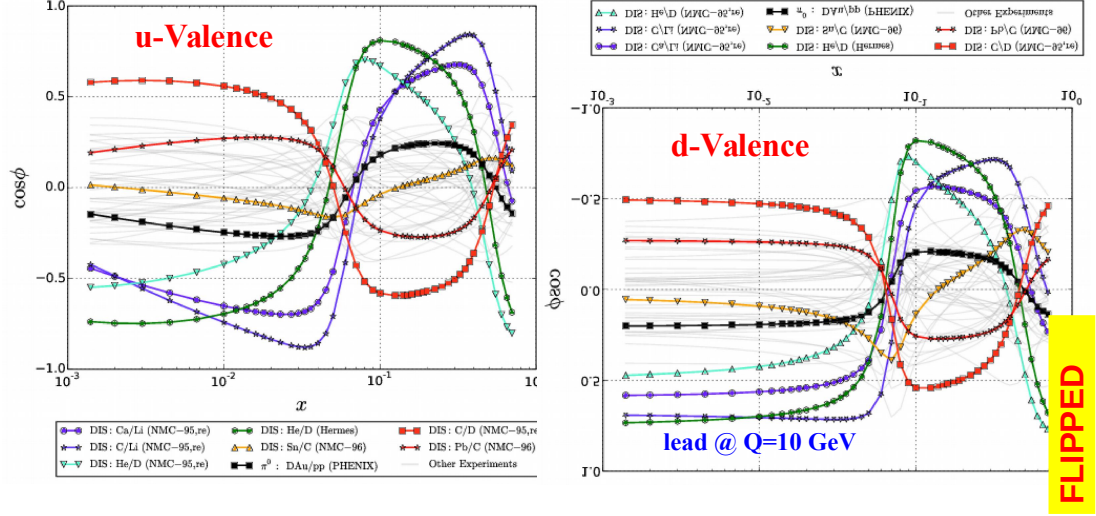


Figure 6: Correlation measures ( $\cos \phi$ ) for  $u_{val}$  (left) and  $d_{val}$  (right) for lead at  $Q = 10 \text{ GeV}$ . Eight selected experiments are highlighted with symbols. To emphasize the anti-correlation between  $u_{val}$  and  $d_{val}$  we have flipped the  $d_{val}$  plot vertically. See Ref. [1] for details.

up and down valence are relatively anti-correlated, we have vertically flipped the plot for the down valence to make the correspondence between the two plots readily apparent. We find that the fit exploits the additional freedom to reduce the  $\chi^2$  by an additional  $\sim 10\%$ . While these are interesting observations, work still remains to definitively distinguish parameterization effects from the underlying physics. In view of the differences, the true nPDF uncertainties should be obtained by combining the results of all analyses and their uncertainties.

## 4 Conclusions

The nCTEQ15 PDFs represent the first complete analysis of nuclear PDFs with errors in the CTEQ framework. The framework used for the nCTEQ15 fit can combine data from both proton and nuclear targets into a single coherent analysis; thus, it can yield more accurate PDFs when using data from nuclear targets.

All in all we find relatively good agreement between different nPDF sets. Most of the noticeable differences occur in regions without any constraints from data and so they can be attributed to different assumptions such as parameterization of the nuclear effects.

Using the nCTEQ15 fit as a reference, it will be interesting to include the upcoming LHC data as we continue to investigate the relations between the proton and the nuclear PDFs.

## ACKNOWLEDGMENTS

I am pleased to thank D. B. Clark, E. Godat, T. Jezo, C. Keppel, K. Kovařik, A. Kusina, F. Lyonnet, P. Nadolsky, J.G. Morfin, J.F. Owens, I. Schienbein, J.Y. Yu for helpful discussions and collaboration.

## References

- [1] K. Kovarik *et al.*, “nCTEQ15 - Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework,” [arXiv:1509.00792](#) [hep-ph].
- [2] A. Kusina, T. Stavreva, S. Berge, F. I. Olness, I. Schienbein, K. Kovarik, T. Jezo, J. Y. Yu, and K. Park, “Strange Quark PDFs and Implications for Drell-Yan Boson Production at the LHC,” *Phys. Rev.* **D85** (2012) 094028, [arXiv:1203.1290](#) [hep-ph].
- [3] K. Kovarik, I. Schienbein, F. I. Olness, J. Y. Yu, C. Keppel, J. G. Morfin, J. F. Owens, and T. Stavreva, “Nuclear corrections in neutrino-nucleus DIS and their compatibility with global NPDF analyses,” *Phys. Rev. Lett.* **106** (2011) 122301, [arXiv:1012.0286](#) [hep-ph].
- [4] I. Schienbein, J. Y. Yu, K. Kovarik, C. Keppel, J. G. Morfin, F. Olness, and J. F. Owens, “PDF Nuclear Corrections for Charged and Neutral Current Processes,” *Phys. Rev.* **D80** (2009) 094004, [arXiv:0907.2357](#) [hep-ph].
- [5] C. Anastasiou, L. J. Dixon, K. Melnikov, and F. Petriello, “High precision QCD at hadron colliders: Electroweak gauge boson rapidity distributions at NNLO,” *Phys. Rev.* **D69** (2004) 094008, [arXiv:hep-ph/0312266](#) [hep-ph].
- [6] **ATLAS** Collaboration, G. Aad *et al.*, “Determination of the strange quark density of the proton from ATLAS measurements of the  $W \rightarrow \ell \nu$  and  $Z \rightarrow \ell \ell$  cross sections,” *Phys. Rev. Lett.* **109** (2012) 012001, [arXiv:1203.4051](#) [hep-ex].
- [7] M. Hirai, S. Kumano, and T.-H. Nagai, “Determination of nuclear parton distribution functions and their uncertainties in next-to-leading order,” *Phys.Rev.* **C76** (2007) 065207, [arXiv:0709.3038](#) [hep-ph].
- [8] K. Eskola, H. Paukkunen, and C. Salgado, “EPS09: A New Generation of NLO and LO Nuclear Parton Distribution Functions,” *JHEP* **0904** (2009) 065, [arXiv:0902.4154](#) [hep-ph].

- [9] D. de Florian, R. Sassot, P. Zurita, and M. Stratmann, “Global Analysis of Nuclear Parton Distributions,” *Phys.Rev.* **D85** (2012) 074028, [arXiv:1112.6324 \[hep-ph\]](#).